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Relationship of ground-level aerosol concentration and atmospheric electric field at three observation sites in the Arctic, Antarctic and Europe

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ABSTRACT

Aerosol number concentrations in the particle size range from ~10 nm to 1 μm and vertical electric field strength in the surface layer was measured between September 2012 and December 2013 at three observation sites: mid-latitude station Swider, Poland, and, for the first time, in Hornsund in the Arctic, Spitsbergen, and the Antarctic Arctowski station in the South Shetland Islands. The measurements of aerosol concentrations have been performed simultaneously with measurements of the electric field with the aim to assess the local effect of aerosol on the electric field E_z near the ground at the three stations which at present form a network of atmospheric electricity observatories. Measurements have been made regardless of weather conditions at Swider and Arctowski station and mostly on fair-weather days at Hornsund station.

The monthly mean particle number concentrations varied between 580 and 2100 particles cm^{-3} at Arctowski, between 90 and 1270 particles cm^{-3} in Hornsund, and between 6700 and 14,000 particles cm^{-3} in the middle latitude station Swider. Average diurnal variations of the ground-level electric field E_z and particle number concentrations in fair-weather conditions were independent of each other for Arctowski and Hornsund stations. At Swider station the diurnal variation is usually characterized by an increase of aerosol concentration in the evening which results in the increased electric field. The assumption of neglecting the influence of varying aerosol concentration on the variation of the electric field in the polar regions, often adopted in studies, is confirmed here by the observations at Arctowski and Hornsund.

The results of aerosol observations are also compared with modelled aerosol concentrations for global atmospheric electric circuit models.

1. Introduction

The Earth's atmospheric electric field which is the manifestation of the flow of electrical current in the weakly conducting atmosphere — the global atmospheric electric circuit (GEC) is present globally but varies spatially and in time (e.g. Rycroft et al., 2000). In reality the ground-level vertical component of this electric field or the equivalent electric potential gradient contains signals which may be divided into three main components: global, regional and local. The amplitudes of these components depend on the location of the measurement site (e.g. polar, oceanic, land) and the local time. The global component of the atmospheric electric field will dominate in places where in addition to the conditions of low turbulent mixing in the planetary boundary layer aerosol concentration is low and fairly constant in time and weather conditions are stable. The choice of the measurement site to study global effects proves to be rather difficult as stations on land and oceanic islands, in high-mountain or polar region are characterized by different levels of meteorological noise. These local effects can be reduced by performing measurements above the planetary boundary layer or by using appropriate procedures for ground-based measurements in so called fair-weather conditions (e.g. Michnowski, 1998).

Eqs. (1)–(7) describe the mathematical relationship between aerosol and atmospheric electricity, in fair-weather conditions and the absence of intense atmospheric convection, related by the Ohm's law (1), the ion balance equation for steady state (2), and the Gauss law (3) (Israël, 1973a). The atmospheric electricity parameters E_z, J_z, λ, and the electric charge density ρ are present in these relationships as follows:

$$E_z = \frac{J_z}{\lambda} \tag{1}$$

$$q - \alpha n_1 n_2 - \beta n_{1,2} Z = 0 \tag{2}$$

$$\frac{dE_z}{dz} = \frac{\rho}{\epsilon_0} \tag{3}$$

$$E_z = \frac{V_I}{\lambda R_{col}} \tag{4}$$

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where

$$\lambda = e(n_1k_1 + n_2k_2) \tag{5}$$

$$Z = N_0 + N_1 + N_2 \tag{6}$$

$$\rho = e(n_1 - n_2) + e(N_1 - N_2). \tag{7}$$

Parameters n_1, n_2 are the positive and negative small ion concentrations, k_1, k_2 are the mobilities of small positive and negative ions and e is the elementary charge. The diameters of small ions are between 10^{-10} and 10^{-9} m and the diameters of large ions are between $5 \cdot 10^{-9}$ and $3 \cdot 10^{-8}$ m. Small ions mobility at sea level is about 10^{-4} m ^{2} V $^{-1}$ s $^{-1}$ and the large ions have three times lower mobility than the small ions (Israël, 1973a). Parameters N_0, N_1, N_2, Z are concentrations of uncharged aerosol, large positive and large negative ions, and total aerosol concentration, respectively, q is the small ion production rate, α is the ion-ion recombination coefficient, and β is the ion-aerosol attachment coefficient, ϵ_0 is the permittivity of free space, i.e. $8.85 \cdot 10^{-12}$ F/m. R_{col} is the electrical resistance of a column of the air of unit surface area.

Eq. (4), which is another version of Eq. (1), describes the relationship between the ionospheric potential, V_I, the vertical electric field, E_z, and the height conductivity profile hidden in the two parameters: air conductivity λ and columnar resistance R_{col}. Aerosol can affect both the (surface) conductivity as well as the column resistance, masking the variations of ionospheric potential in the observed electric field or the potential gradient at the ground. At ground level an increase in aerosol concentrations Z may cause a decrease of the atmospheric electric conductivity λ and an increase of the electric field E_z. Aerosols decrease air conductivity by decreasing the ion mobility. This process is dependent on aerosol particle composition, their size and electric charge accumulated on aerosol. When aerosol attachment dominates over recombination the electric charge on aerosol particles also affects the electric field in accordance with the Gauss law – Eq. (3). In strongly polluted air, the non-linear relationship (Harrison, 2005) between the surface air conductivity and local columnar resistance R_{col} can have strong influence on the variations of E_z — Eq. (4).

Measurements of the three basic parameters of atmospheric electricity, i.e. the air electric conductivity, λ, vertical atmospheric electric field, E_z (or the potential gradient, PG), and the air-Earth current density, J_z, at a selected site can be used for preliminary assessment of local sources, including aerosol. Due to technical difficulties and weather conditions, not all atmospheric electricity observation stations perform continuous and long-term measurements of λ, E_z, J_z. Particularly in polar regions usually the ground-level atmospheric electric field and rather occasionally the current density or the air electric conductivity are observed. Simultaneous monitoring of aerosol number concentrations with potential gradient observations has also been done rather rarely so far. Aerosol concentration measurements by a condensation counter is rather expensive and therefore it is often performed only from time to time in order to determine the local background aerosol concentrations for the purposes of correct interpretation of the global variation in the observed atmospheric electric field.

Discussion on the influence of the surface aerosol concentrations on atmospheric electricity in polar conditions was presented in only a few of the works. Burns et al. (1995) analysed the effect of local anthropogenic and meteorological parameters on the electric field at the west Antarctic coast at Davis station. They showed that local influence persists there between 03:00 and 10:00 LT and masks the magnetospheric impact on the measured electric field. Deshpande and Kamra (2001) studied λ and Z at the East Antarctic coastal Maitri station and concluded that the fluctuations of the potential gradient were large when aerosol concentrations were higher. Diurnal variations of local potential gradient correlated with aerosol variations. Reddell et al. (2004) presented seasonal variations of E_z and J_z and calculated that the variations of atmospheric conductivity were low at Amundsen-Scott South Pole Station when pollution levels were small.

The number of works on the relationship between the aerosol and atmospheric electricity at mid-latitude land stations and at oceanic stations is much greater than investigating these relationships at polar stations. Seasonal variations of Aitken nuclei, usually defined as particles of diameters between 10^{-9} and 10^{-7} m, and atmospheric electrical conductivity shown in the work of Adlerman and Williams (1996), present highly non-linear relationships between these parameters. In Poona, India, the small changes in aerosol correspond to significant changes in conductivity. On the other hand, in Huancayo, Peru, large variations of the conductivity corresponded to slight changes of aerosol. This shows that many parameters (concentrations of small and large ions and aerosol, ion mobility, as well as the size and composition of aerosol particles) are all important factors in the relationship between the aerosol concentrations and the air electric conductivity.

Mechanisms of the effect of aerosol on atmospheric ions has been presented in the work of Harrison and Carslaw (2003), Yu and Turco (2001), Harrison (2004), Cobb and Wells (1970) and Dhanorkar and Kamra (1997). Many studies have shown that the aerosol coagulation which creates large particles and the aerosol nucleation on ions which causes formations of new particles can substantially affect the atmospheric conductivity due to the increase of the electric charge on large ions and aerosol.

Sheftel et al. (1994) has shown an influence of anthropogenic atmospheric pollution on air conductivity and atmospheric electric field based on the data obtained from several stations located at middle and high latitudes. Diurnal variations of the conductivity were different on weekdays and Sundays. In this view atmospheric electric parameters λ and E_z are good indicators of the atmospheric pollution (Silva et al., 2014). At some stations located in polluted regions variations of E_z can be dominated by the local effects of aerosol. Separating these effects, especially on long-term scales can be complicated (Harrison and Bennett, 2007). Serrano et al. (2006) on the basis of long-term measurements (1955–1991) presents weekly dependence of the electric field at Portela (Lisbon, Portugal) on weekly variations of urban pollution.

The response of the electric field to variations of the ionospheric potential is, according to Eq. (4), also affected by the simultaneous variations of atmospheric conductivity and columnar resistance, which in turn are sensitive to variations of the height profile of aerosol concentrations. Based on measurements at Kew Observatory (London) and a model, Harrison (2005) showed that relations of columnar resistance R_{col} and conductivity λ were non-linear. An increase of λ only initially resulted in a decrease of R_{col} which later remained constant with still increasing λ. For individual days and during strong turbulent mixing the relationship between λ and R_{col} can be complicated which further affects the interpretation of diurnal variations of E_z as variations of V_I.

The annual variation of E_z at a land station may have maximum in the local winter resulting from increased local aerosol and dust concentrations (Kubicki et al., 2007). During this period the measured electric field can mainly contain the local component. In polluted areas and on summer days the diurnal variation of E_z has a double maximum consistent with maximum aerosol concentration, and E_z has a minimum at noon, as a result of strong turbulent mixing. In connection with this effect Kubicki (2011) showed that evaluation of global effects on the basis of the vertical current measurements is still possible during conditions of forced convection in the planetary boundary layer and at high aerosol concentrations; this has been further studied in Kubicki and Sorbjan (2015). Atmospheric convection can also play a major role in shaping the vertical profile of aerosol concentrations in polar regions. The large difference in the surface and air temperature affects the conversion processes of aerosol (e.g. Shaw, 1998).

In this work we present analysis of ground-level aerosol concentration, meteorological parameters and atmospheric electricity parameters in the three locations: Arctowski, Hornsund and Swider observation stations, made between September 2012 and December 2013. The aerosol